

COHERENCE PHENOMENA IN K-SHELL IONIZATION AND CHARACTERISTIC RADIATION BY HIGH-ENERGY PARTICLES AND ULTRASHORT ELECTRON BUNCHES IN CRYSTALLINE AND AMORPHOUS TARGETS

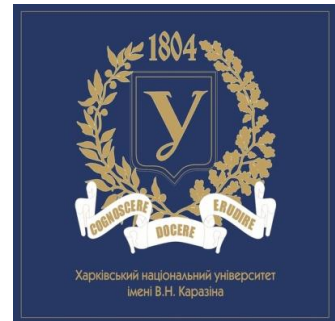


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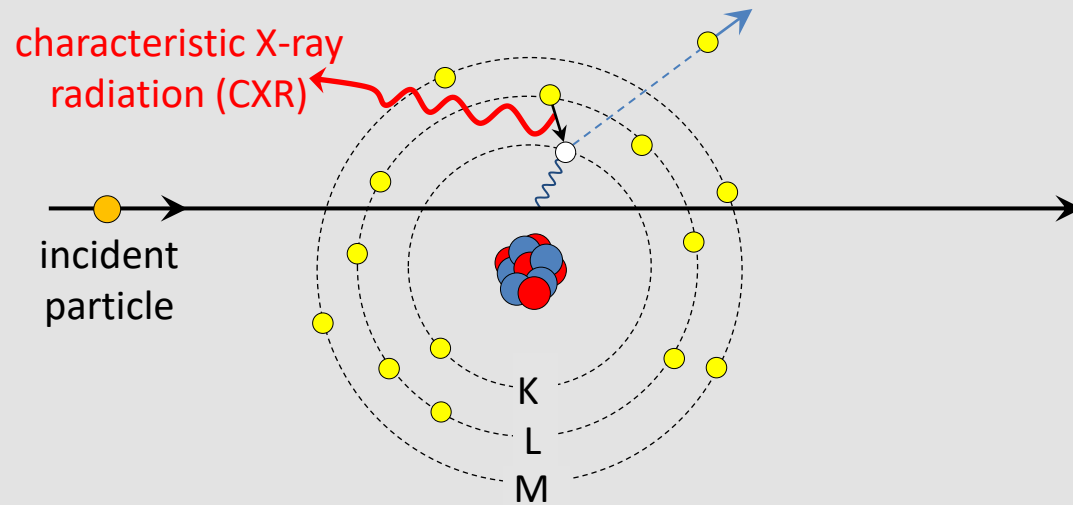
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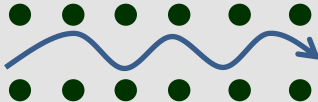
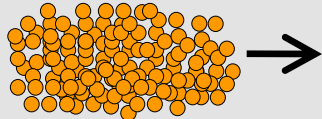
Kharkiv, Ukraine



*French-Ukrainian workshop, IJCLab, Paris-Saclay University,
Orsay, France, 12-14 October 2026*



Two types of coherent effects in K-shell ionization and CXR:

- ✓ Coherent interactions of a single incident particle with periodically arranged atoms in oriented crystals
(coherence due to periodicity)
 
- ✓ Coherent interaction of an ultrashort (sub-fs) electron bunch with a single atom in an amorphous target
(coherence due to interference between electromagnetic fields of different electrons in the bunch)
 

Potential practical importance:

- ✓ Nondestructive tools for choosing optimal crystal orientation with respect to the beam
- ✓ New methods for diagnostics of sub-fs bunches and microbunched beams

OUTLINE OF THE TALK

K-shell ionization and CXR by ...

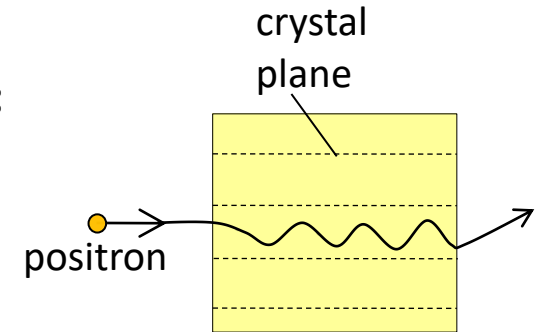
- ... e^- and e^+ in oriented crystals
- ... ultrashort electron bunches in amorphous targets
- ... 'half-bare' electron – experiment at DESY

Experiments on ultrarelativistic particle CXR in oriented crystals:

J. F. Bak et al., Phys. Rev. A 25, 1334 (1982)

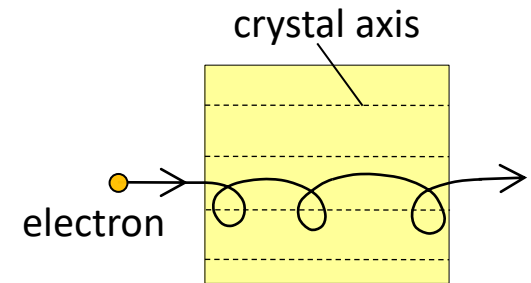
A. N. Aleinik et al., Pis'ma Zh. Tekh. Fiz. 13, 1367 (1987)

M. Andreyashkin et al., NIMB 173, 142 (2001)



Analytical treatment (K-shell ionization):

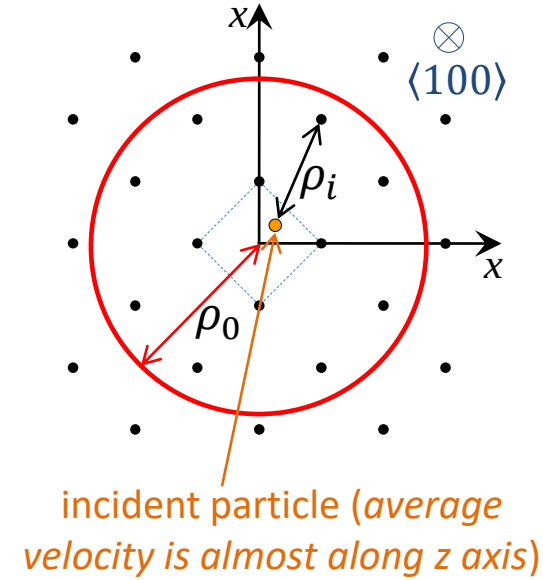
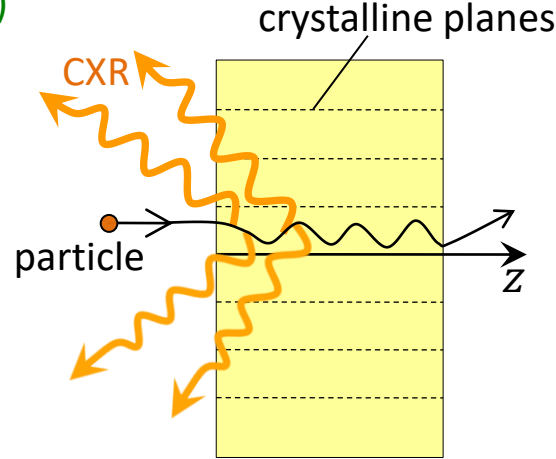
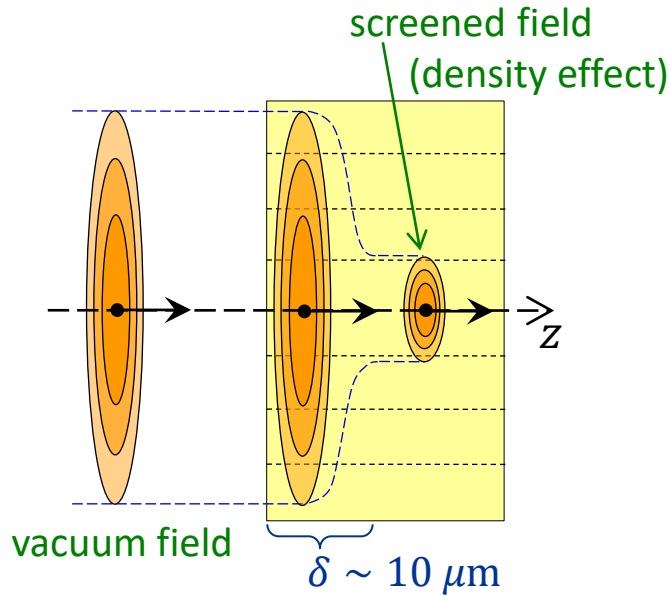
S. M. Darbinian, K. A. Ispirian, Rad. Eff. 62, 207 (1982)



Aims of the work:

- ✓ development of methods for computer simulations of K-shell ionization rates and CXR in oriented crystals
- ✓ studying evolution of characteristics of these processes with the change of crystal orientation with respect to the incident beam

METHOD OF SIMULATION OF K-SHELL IONIZATION AND CXR IN ORIENTED CRYSTALS



Equivalent photon spectrum for the field around the particle:

$$\frac{dN_{ph}}{d\omega} = \frac{2\alpha}{\pi\omega} \left\{ \ln \frac{1}{\omega_p \rho_0} - \frac{1}{2} + \left[\ln \frac{\gamma \omega_p}{\omega} - 1 \right] e^{-\mu z} + \left[\cos(\lambda_\gamma + \lambda_p) - \lambda_p \left[\frac{\pi}{2} - \text{Si}(\lambda_\gamma + \lambda_p) \right] \right] e^{-\mu z/2} \right\}$$

$$\lambda_\gamma = \omega z / 2\gamma^2 \quad \lambda_p = \omega_p^2 z / 2\omega$$

Number of K-shell ionization events per unit path:

$$N_i(x, y) = \frac{4\pi e^4}{mc^2} \left\{ \frac{n}{\pi \eta \bar{\epsilon}} \sum_{\rho_i < \rho_0} \frac{1 - e^{-\rho_i^2/b^2}}{\rho_i^2} + \frac{mc^2 n}{4\pi e^4} \int_{\omega_K}^{\infty} \frac{dN_{ph}}{d\omega} \sigma_{ph}^K(\omega) d\omega + \frac{n(x, y)}{\hbar \omega_K} \right\}$$

$$\bar{\epsilon} = \frac{4\pi^2 e^2 \hbar}{mc} \left(\int_{\omega_K}^{\omega_{\max}} \sigma_{ph}^K(\omega) \frac{d\omega}{\omega} \right)^{-1}$$

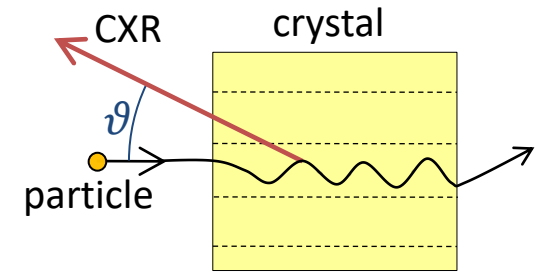
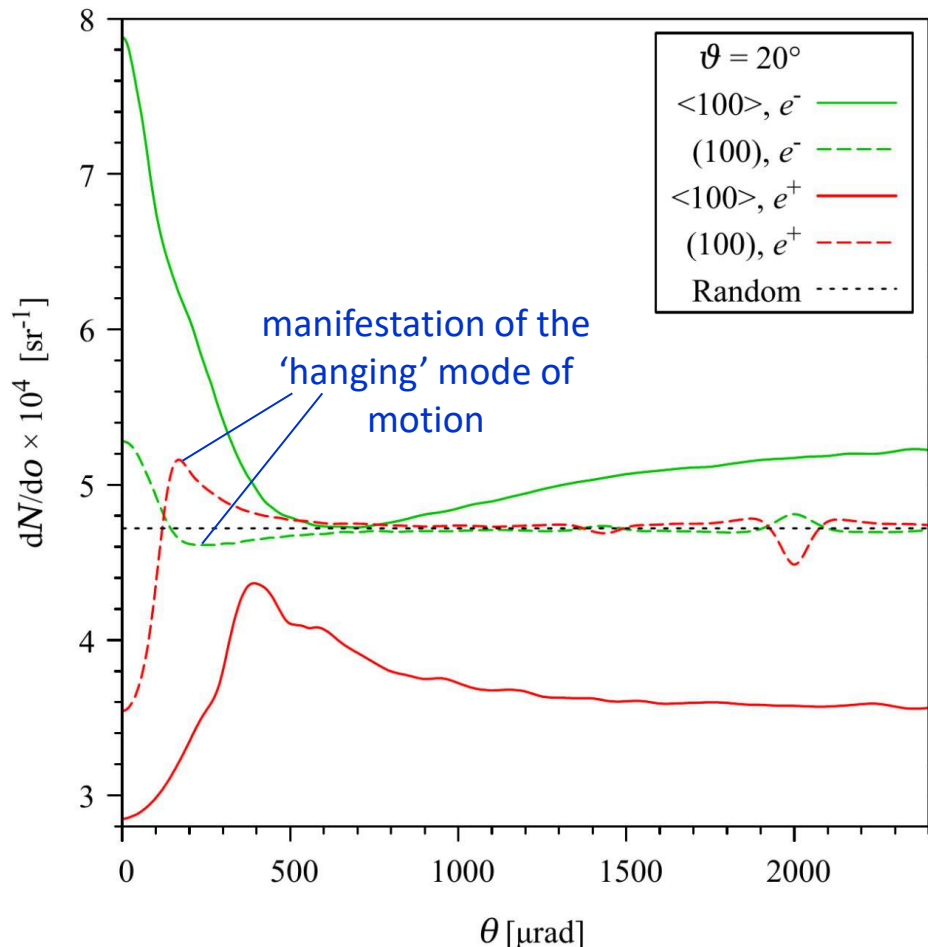
$n(x, y)$ – local concentration of K-shell electrons
 $\sigma_{ph}^K(\omega)$ – K-shell photoionization cross-section

ORIENTATIONAL EFFECTS FOR CXR IN A SILICON CRYSTAL

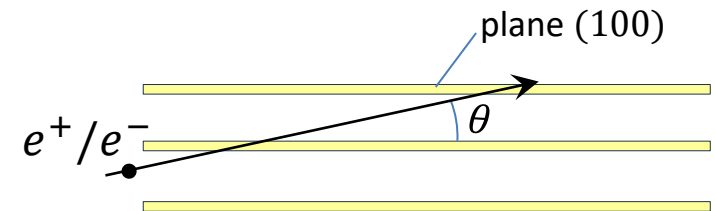
CXR angular density:

$$\frac{dN}{d\omega} = \frac{w_f P_\alpha}{4\pi} \int N_i(z) e^{-\mu(\omega_{CXR})z/\cos\vartheta} dz$$

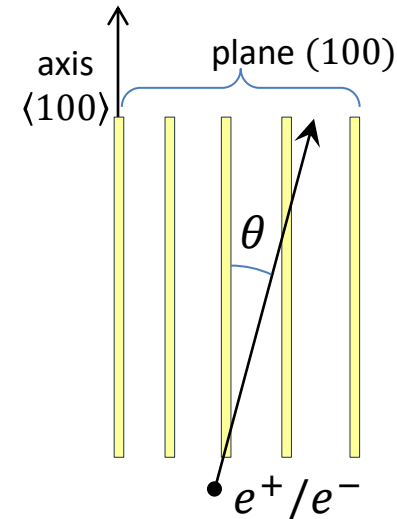
Dependence of the angular density of the number of CXR photons at $\vartheta = 20^\circ$ on the angle θ between 1 GeV electron/positron momentum and the crystal axis $\langle 100 \rangle$ or crystal plane (100):



For planar orientation:



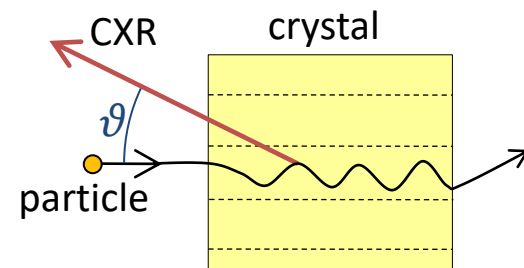
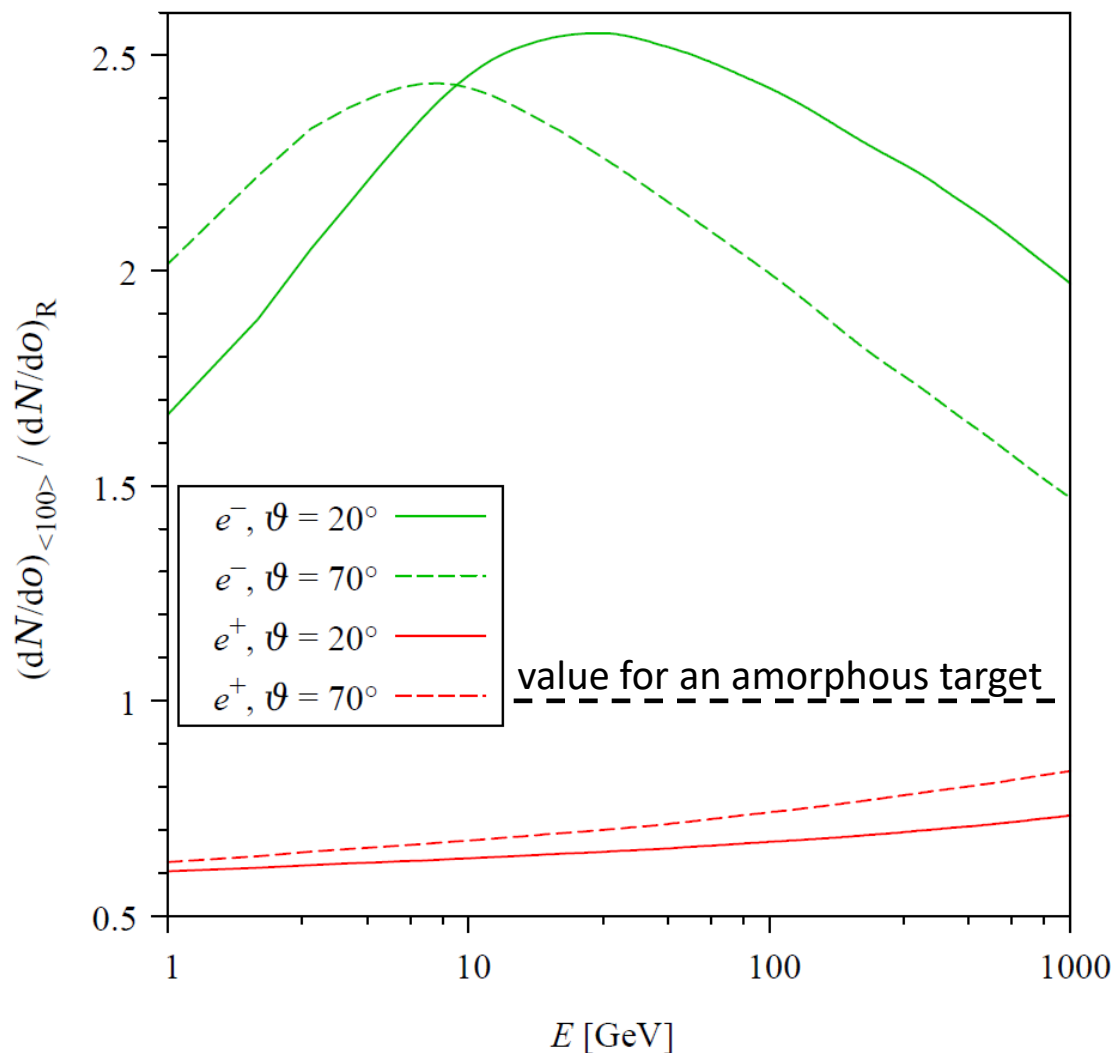
For axial orientation:



ENERGY DEPENDENCE OF CXR YIELD FOR $\langle 100 \rangle$ AXIAL ORIENTATION

S.V. Trofymenko, I.V. Kyryllin, Phys. Rev. A 113, 032808 (2026)

Dependence of the angular density of the number of CXR photons emitted from the upstream surface of the crystal, normalized by its value in the amorphous target, on the particle energy:



$(dN/do)_{\langle 100 \rangle}$ – CXR angular density for the axial $\langle 100 \rangle$ orientation

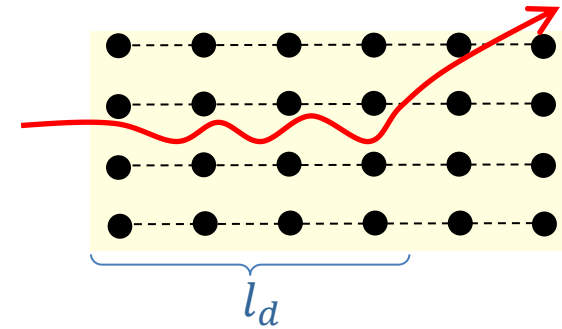
$(dN/do)_R$ – CXR angular density for an amorphous target (random crystal orientation)

Maximum for e^- is a result of “competition” of dechanneling and Lorentz enhancement of the particle’s Coulomb field

DECHANNELING LENGTH OF e^- AND π^-

$l_d \approx \xi E$ — length at which $1/e \approx 0.37$ of particles still remains channeled (**large uncertainty in the value of ξ**)

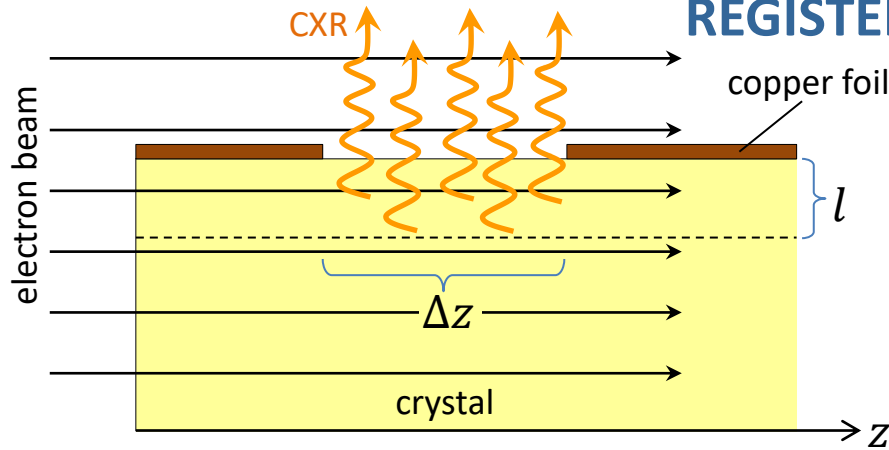
Plane	Particles	$E(\text{GeV})$	$\xi (\mu\text{m}/\text{GeV})$	Refs.
(110)	e^-		17.8	[1]
(110)	e^-	0.855	21.1	[2]
(110)	e^-	0.855	48.0	[3]
(110)	e^-	0.855	9.7	[4]
(110)	e^-	1.2	24.2	[5]
(110)	π^-	150	6.2	[6]
(111)	e^-		23.6	[1]
(111)	e^-	0.855	23.7	[7]
(111)	e^-	0.855	15.9	[4]
(111)	e^-	3.35-14	15.3	[8]
(111)	e^-	0.5-100	27	[9]
(111)	e^-	50	6.6	[10]
(111)	e^-	0.27-1.2	6	[11]



1. V. Baier et al., Electromagnetic Processes at High Energies in Oriented Single Crystals, 1998
2. H. Backe et al., NIMB, 2008
3. W. Lauth et al., Int. J. Mod. Phys. A, 2010
4. A. Kostyuk et al., J. Phys. B, 2011
5. V.I. Vit'ko, G.D. Kovalenko, JETP, 1988
6. W. Scandale et al., Phys. Lett. B, 2013
7. A. Mazzolari et al., Phys. Rev. Lett., 2014
8. T.N. Wistisen et al., Phys. Rev. Accel. Beams 2016
9. M. Tabrizi et al., Phys. Rev. Lett., 2007
10. V.M. Biryukov, arXiv:0712.3904, 2007
11. S.P. Fomin et al., NIMB, 1997

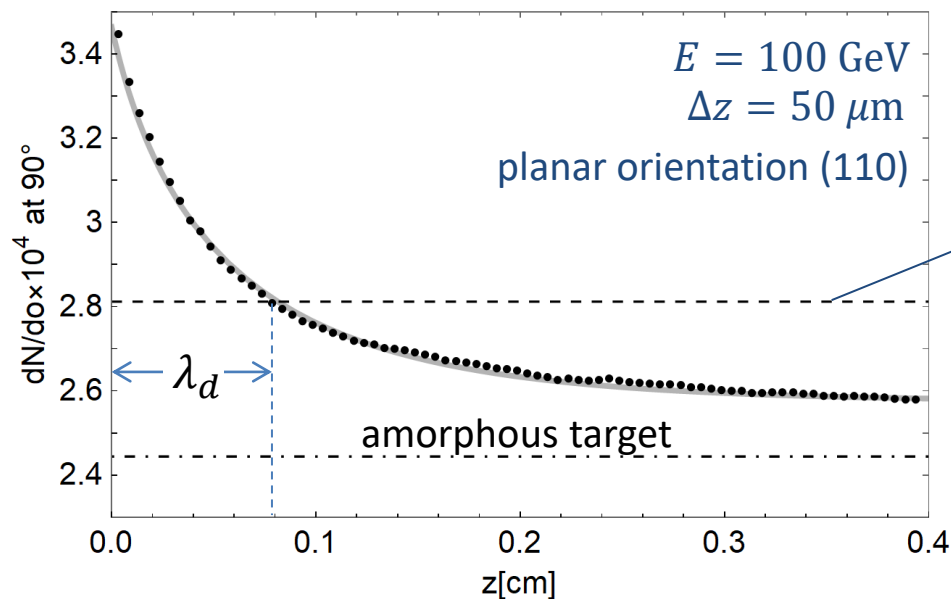
*S.V. Trofymenko , I.V. Kyryllin, Eur. Phys. J. C, 80 (2020) 689
(proposal of l_d measurement based on ion. loss spectra)*

POSSIBILITY OF THE DECHANNELING LENGTH MEASUREMENT REGISTERING CXR



S.V. Trofymenko, I.V. Kyryllin, Probl. At. Sci. Tech. 163, 55 (2026)

Possibility of obtaining sufficient CXR intensity for sufficiently small Δz for electron energies larger than 20 GeV



Dots: Dependence of the angular density of CXR from the slit Δz on the slit position

Solid line: fitting

the value of dN/do , which differs from the 'amorphous' value e times smaller than dN/do at $z=0$

E(GeV)	l_d (mm)	λ_d (mm)	λ_d/l_d
50	0.68	0.39	0.57
100	1.45	0.8	0.55
200	2.72	1.47	0.54

l_d – dechanneling length from simulation of the number of channeled particles

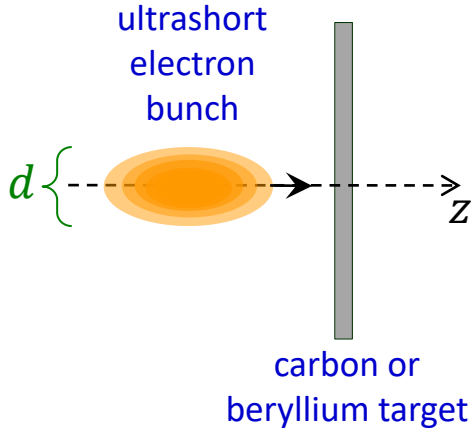
λ_d – dechanneling length from CXR

The coefficient $\eta = \lambda_d/l_d$ is almost energy independent

K-shell ionization and CXR by ...

- ... e^- and e^+ in oriented crystals
- ... ultrashort electron bunches in amorphous targets
- ... 'half-bare' electron – experiment at DESY

K-SHELL IONIZATION BY ULTRASHORT ELECTRON BUNCH IN ULTRATHIN TARGET



Total cross section (distant + close collisions):

$$\sigma = \sigma_d + \sigma_c$$

Cross section (distant collisions) in the equivalent photon method:

$$\sigma_d = \frac{1}{N} \int \frac{dN_{ph}}{d\omega} \sigma_{ph}^K(\omega) d\omega$$

$\sigma_{ph}^K(\omega)$ – K-shell photoionization cross section

Equivalent photon method for K-shell ionization:

Bak J.F. et al. // Phys. Scr. 1986

Sørensen A.H. // Phys. Rev. A. 1987

Equivalent photon spectrum of the field around the bunch:

$$\frac{dN_{ph}}{d\omega} = (4\pi^2 \hbar \omega)^{-1} \int_{\rho_0}^{\infty} |\mathbf{E}_{\omega}(\mathbf{r})|^2 2\pi \rho d\rho$$

$$\frac{dN_{ph}(\omega)}{d\omega} = \frac{2\alpha N}{\pi\omega} \left\{ \underbrace{\ln \frac{\gamma}{\omega \rho_0} - \frac{1}{2}}_{\text{incoherent part (sum of single-electron spectra)}} + \underbrace{(N-1)F_{\parallel}(\omega)\psi(\omega, d)}_{\text{coherent part (interference of single-electron fields)}} \right\}$$

incoherent part (sum of single-electron spectra)

coherent part (interference of single-electron fields)

$$\psi(\omega, d) = -\{1 + e^a(1 + a)\text{Ei}(-a)\}/2$$

$$a = d^2 \omega^2 / \gamma^2$$

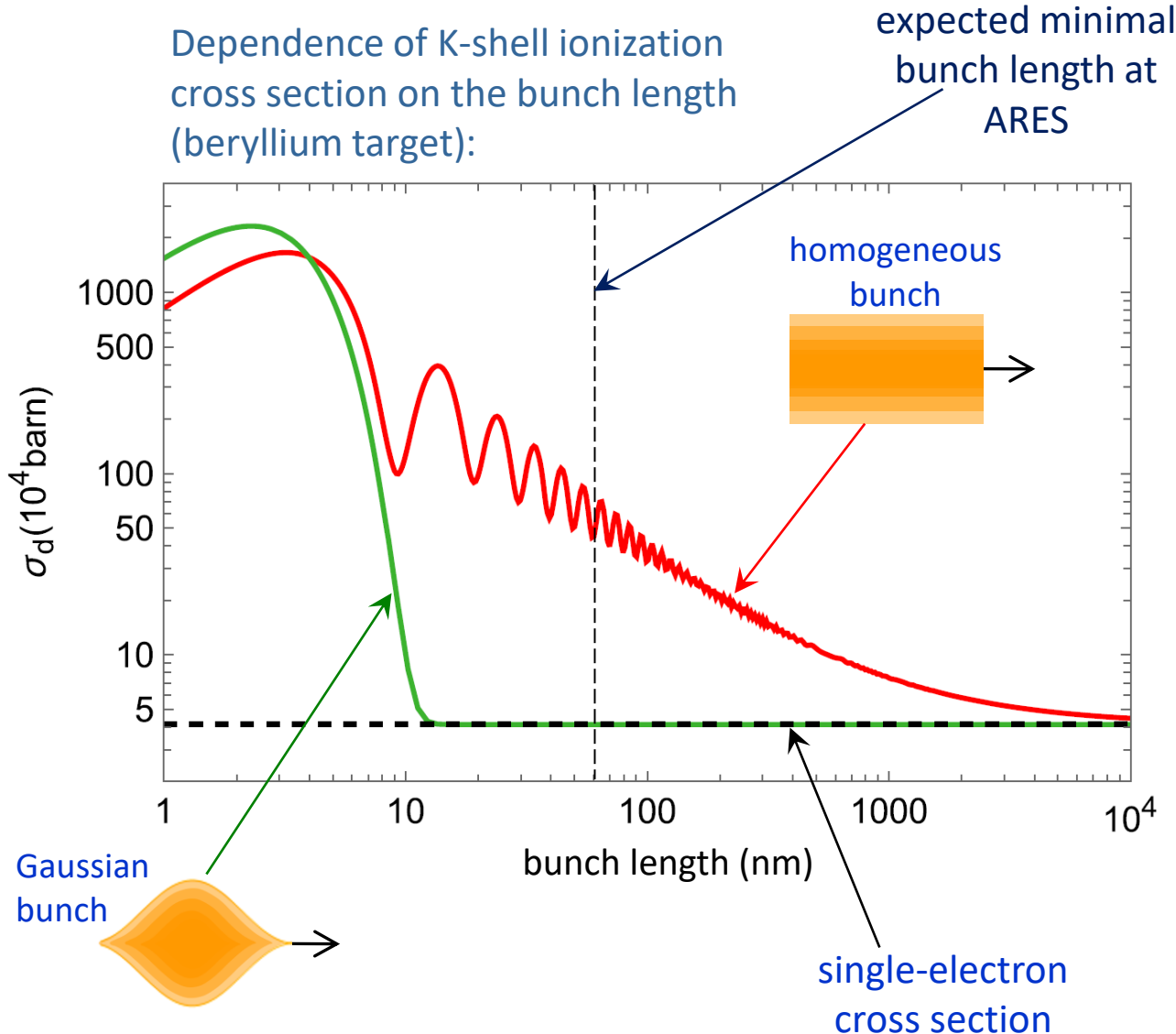
$$F_{\parallel}(\omega) = \left| \int f_{\parallel}(z) e^{-i\omega z/v} dz \right|^2 - \text{longitudinal form-factor}$$

$f_{\parallel}(z)$ – particle density distribution

BUNCHES WITH GAUSSIAN AND HOMOGENEOUS LONGITUDINAL PARTICLE DISTRIBUTION

S.V. Trofymenko, V.S. Skorobohatov, Phys. Lett. A 572, 131319 (2026)

Dependence of K-shell ionization cross section on the bunch length (beryllium target):



Parameters are typical for ARES (DESY):

$$\varepsilon = 100 \text{ MeV}$$

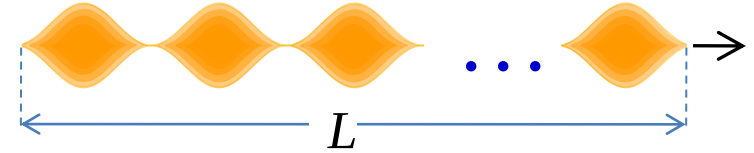
$$d = 0.75 \text{ } \mu\text{m}$$

$Q \approx 0.75 \text{ pC}$ for 130 nm bunch length and linearly changes with length

Possibility of increasing K-shell ionization cross section by several orders of magnitude in light-element targets

MICROBUNCHED BEAM (RESONANCE EFFECT)

beam longitudinal
form-factor: $F_{\parallel}(\omega) = \left(\frac{8\pi^2 s^2}{\omega L^3} \right)^2 \frac{\sin^2(\pi s \omega / \omega_s)}{(\omega^2 - \omega_s^2)^2}$



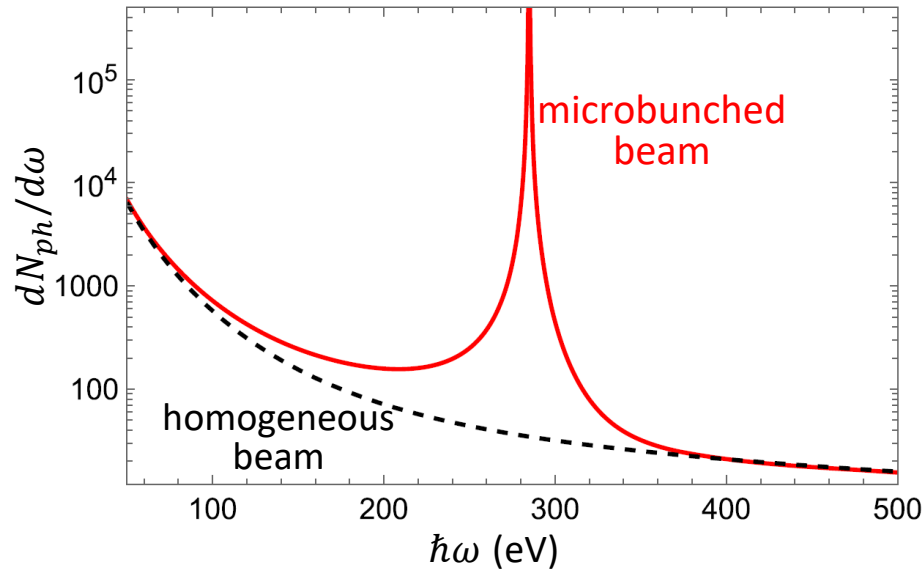
s – number of microbunches in the beam

$$\omega_s = 2\pi s / L$$

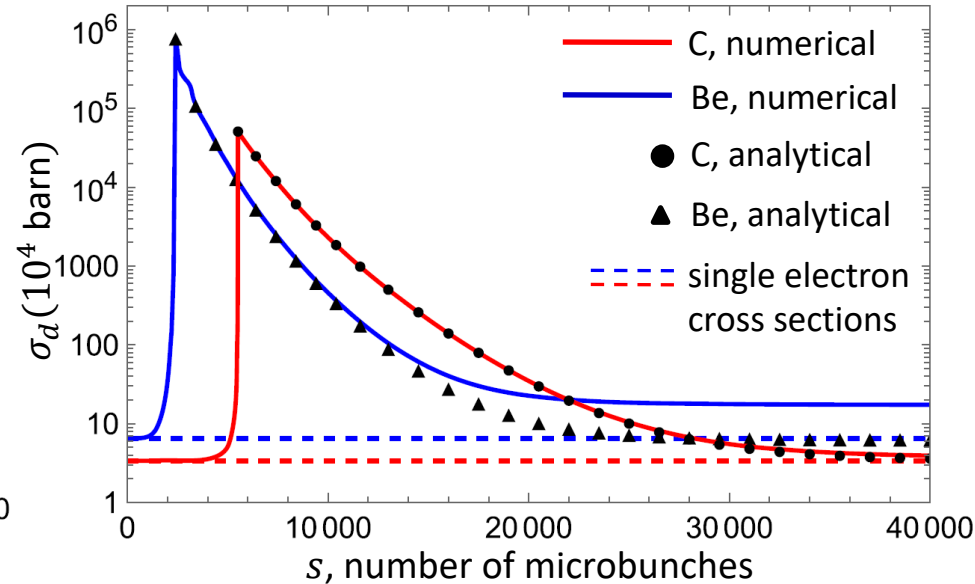
Parameters are typical for European XFEL:

$$\varepsilon = 17.5 \text{ GeV}, d = 30 \text{ } \mu\text{m}, L = 24 \text{ } \mu\text{m}, Q = 1 \text{ nC}$$

Equivalent photon spectrum:



K-shell ionization cross section in
carbon and beryllium targets:



analytical approximation for cross section: $\sigma_d^{coh}(s) = \frac{\alpha}{2\pi s} (N - 1) \sigma_K^{ph}(\omega_s) \psi(\omega_s, d)$

$$\psi(\omega, d) = -\{1 + e^a(1 + a)\text{Ei}(-a)\}/2$$

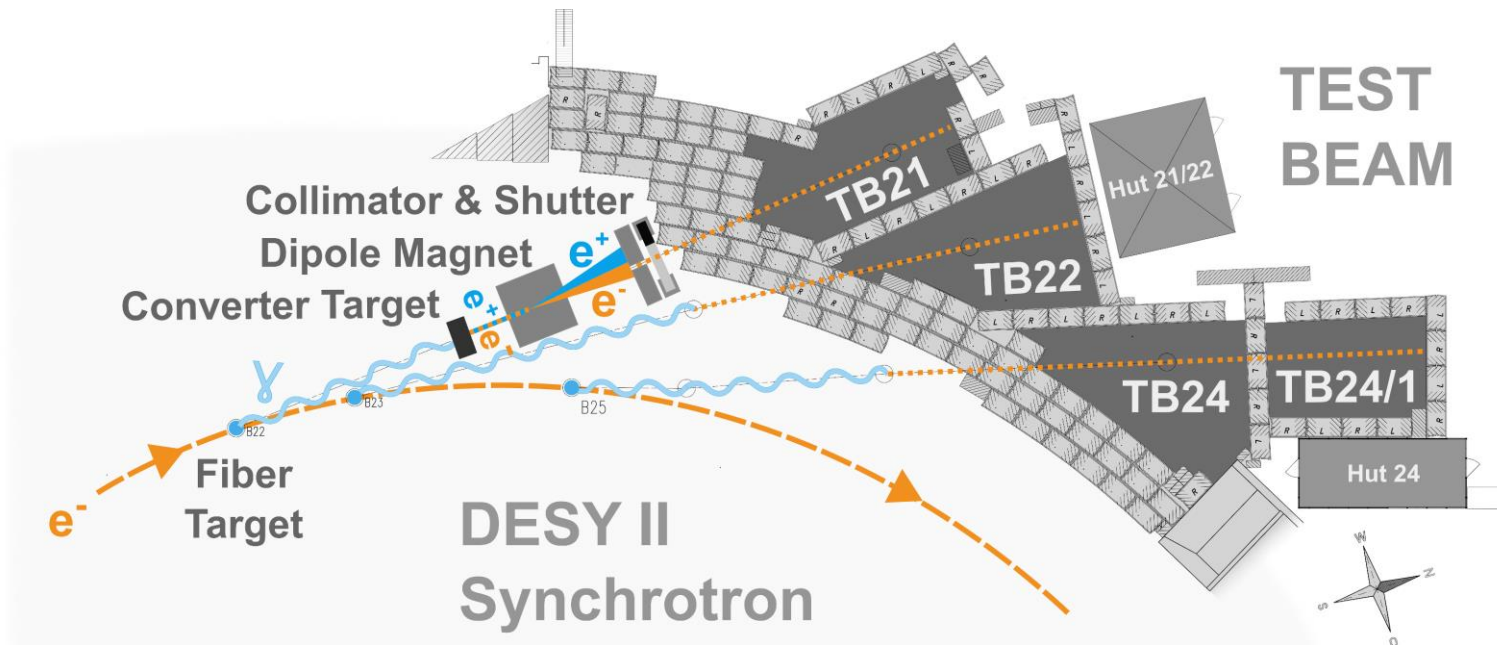
$$a = d^2 \omega^2 / \gamma^2$$

K-shell ionization and CXR by ...

- ... e^- and e^+ in oriented crystals
- ... ultrashort electron bunches in amorphous targets
- ... 'half-bare' electron – experiment at DESY

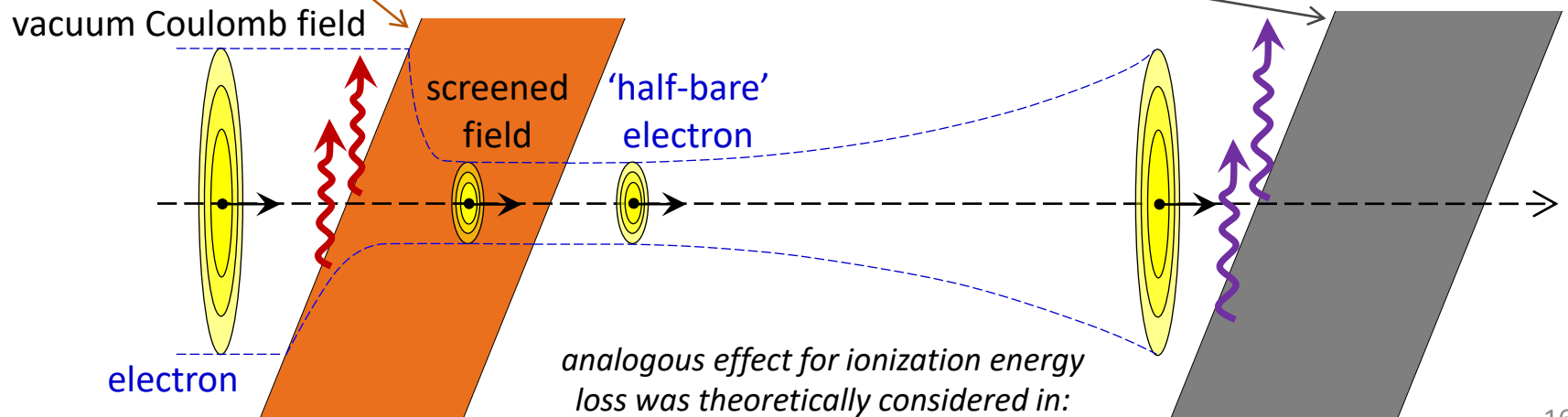
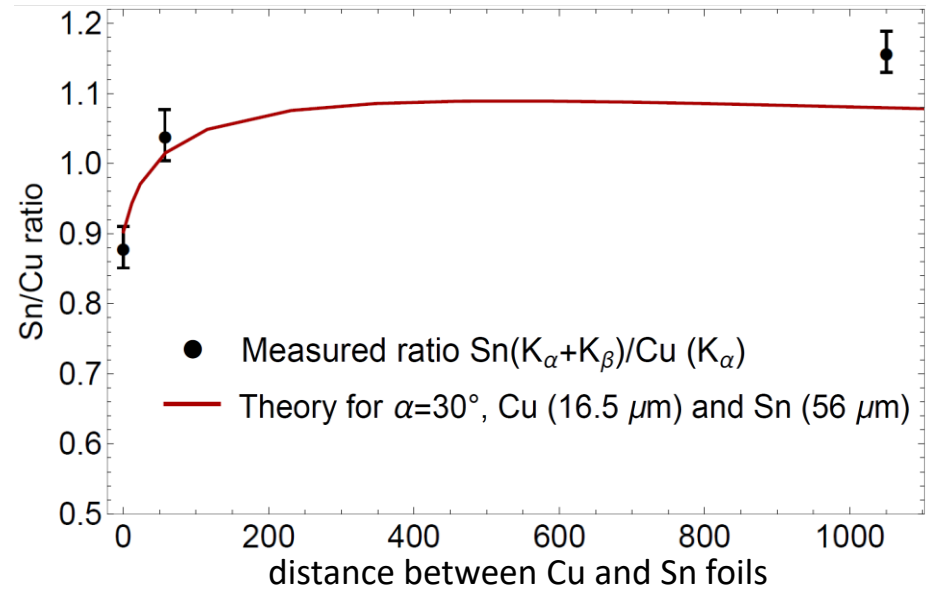
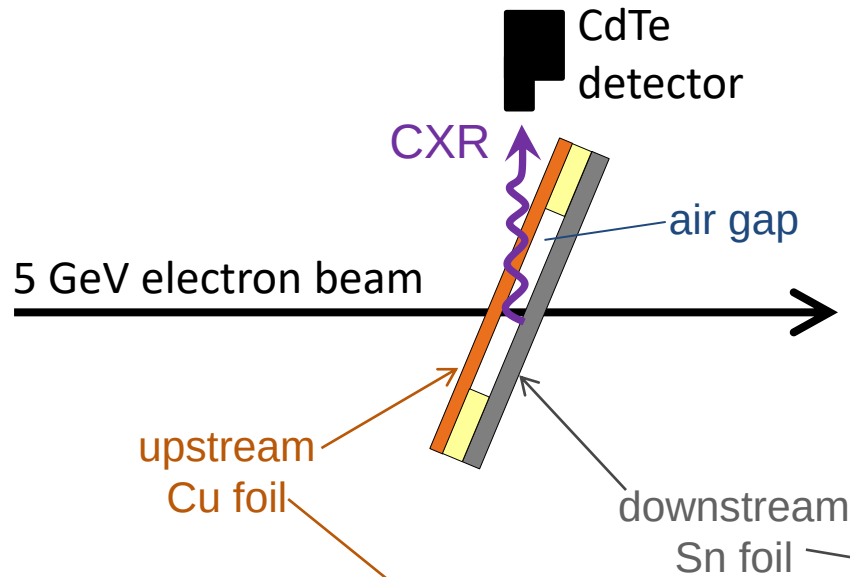


EXPERIMENTAL EVIDENCE OF ‘HALF-BARE’ ELECTRON MANIFESTATION IN K-SHELL IONIZATION (experiment at DESY TB-21)



EXPERIMENTAL EVIDENCE OF 'HALF-BARE' ELECTRON MANIFESTATION IN K-SHELL IONIZATION (experiment at DESY TB-21)

People involved: S. Trofymenko, Yu. Kazarinov, I. Kyryllin, M. Malovytsia, M. Bondarenko, A. Shchagin, G. Kube, A. Novokshonov, V. Skorobohatov et al.

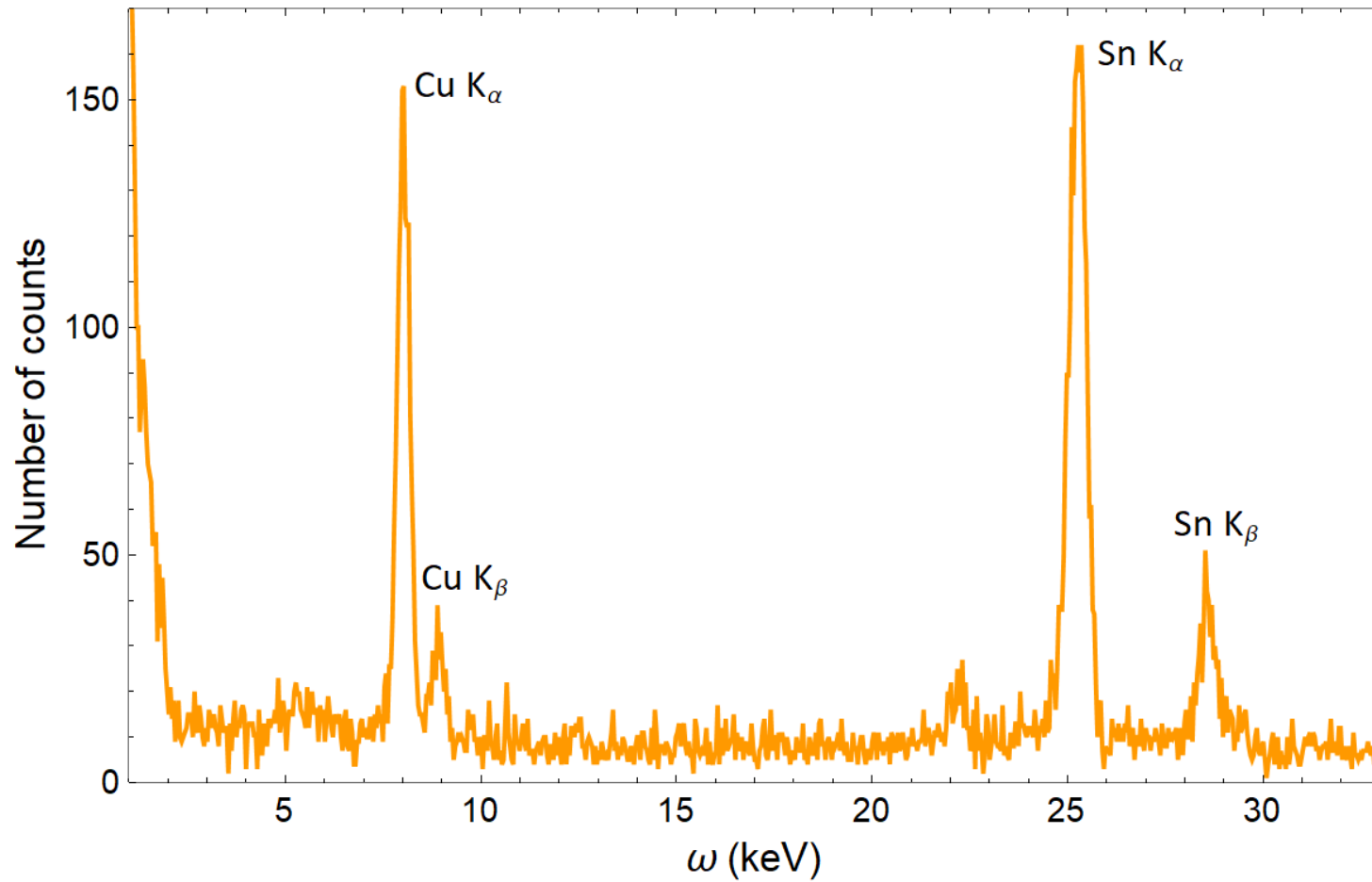


N.F. Shul'ga, S.V. Trofymenko // Phys. Lett. A, 376 (2012) 3572

CONCLUSIONS

- A method of simulation of atomic K shell ionization and characteristic X-ray radiation (CXR) of high-energy particles in oriented crystals is elaborated, taking into account the transition radiation process at the particle entrance into the crystal
- The dependences of the angular distribution of CXR from the upstream surface of the crystal on its orientation relative to the direction of electron/positron motion and on the particle energy in the range of 1 – 1000 GeV are obtained
- New methods for experimental measurement of the dechanneling length of high-energy electrons in a crystal by registering ionization loss spectra and CXR are proposed
- In light-element targets (Be, C) K-shell ionization cross section for ultrashort electron bunches can exceed the corresponding single-electron cross section by an order of magnitude for ARES parameters
- For microbunched beams a resonant effect in K-shell ionization should take place leading to cross section increase by several orders of magnitude for the parameters of European XFEL
- Experimental evidence of ‘half-bare’ electron manifestation in K-shell ionization

Spectrum for 0 μm distance between the foils,
straight beam, total of 5.5 hours of measurement

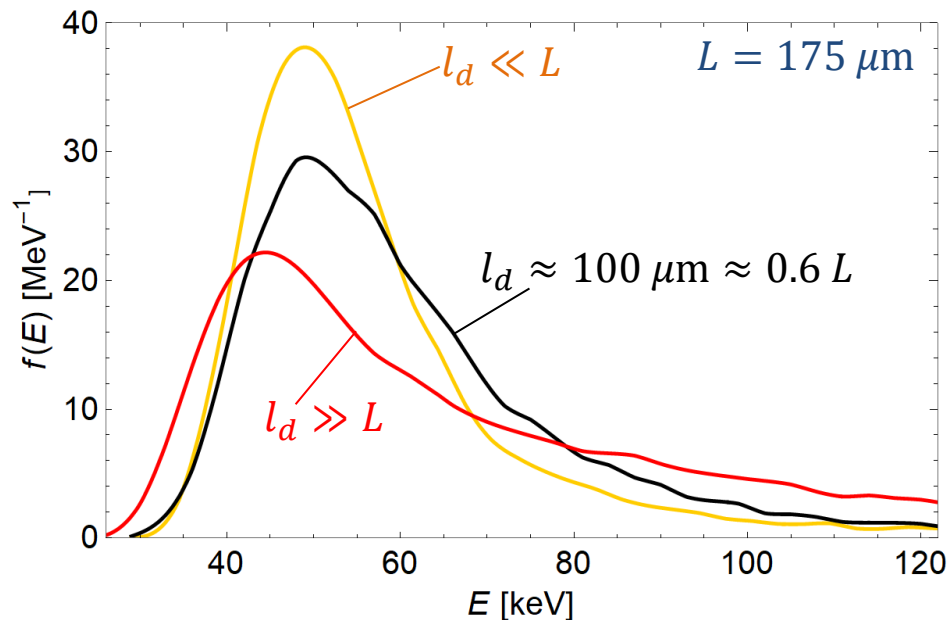


POSSIBILITY OF THE DECHANNELING LENGTH MEASUREMENT REGISTERING THE IONIZATION LOSS SPECTRA

S.V. Trofymenko , I.V. Kyryllin, Eur. Phys. J. C, 80 (2020) 689

(proposal of l_d measurement based on ion. loss spectra)

Ionization loss spectra of 6 GeV electrons in a silicon target of thickness $L = 175 \mu\text{m}$. The particles incident along (110) plane



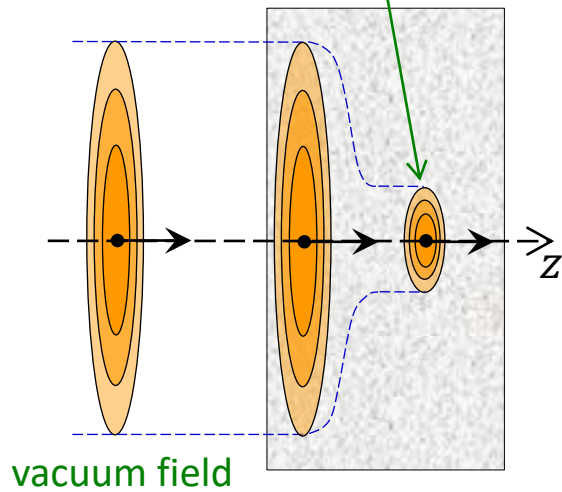
The shape of the spectrum is sensitive to l_d/L

Proposal to apply Si detector with smoothly tunable thickness:

A.V. Shchagin, G. Kube, S.A. Strokov, W. Lauth, NIM A 1059 (2024) 168930

screened field (density effect)

MICROBUNCHED BEAM (THICK TARGETS)



Screening of the field leads to the disappearance of coherent effects on distance which depends on the number of microbunches!



K-shell ionization cross section as a function of depth z for different numbers of microbunches:

